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United States Patent

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Simmons et al.

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(54) **PUMP HAVING OPPOSING MAGNETS BETWEEN A ROTOR AND STATOR, AND RELATED ASSEMBLIES, SYSTEMS, AND METHODS**

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(51) **Int. Cl.**

F04D 13/06 (2006.01)
F04D 13/02 (2006.01)

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CPC ***F04D 13/06*** (2013.01); ***F04D 13/024*** (2013.01); ***F04D 13/026*** (2013.01);

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(58) **Field of Classification Search**

CPC F04D 13/06; F04D 13/0633; F04D 13/026; F04D 13/027; F04D 13/024;

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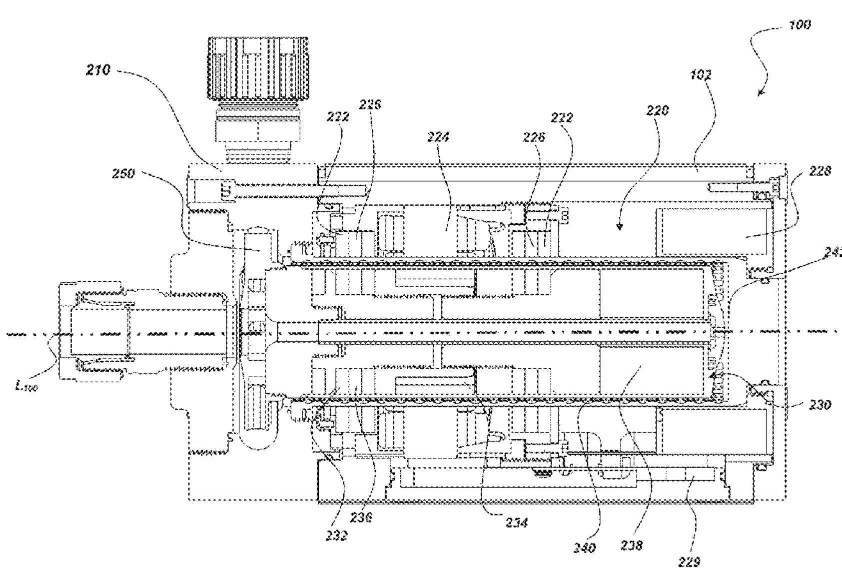
(57) **ABSTRACT**

A pump may include a stator, a rotor, and an impeller. The stator may include one or more electromagnets and one or more permanent magnets. The rotor may include an armature, one or more complementary permanent magnets, and a pull magnet configured to position the rotor in an axial direction. The rotor may be disposed within the stator. The complementary permanent magnets and the one or more permanent magnets of the stator may create magnetic bearings. The armature may be aligned with at least one of the electromagnets of the stator and configured to rotate the rotor with respect to the stator. The impeller may be coupled to the rotor.

18 Claims, 10 Drawing Sheets



Related U.S. Application Data

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(51) **Int. Cl.**
F04D 25/02 (2006.01)
F04D 29/058 (2006.01)
F16C 32/04 (2006.01)
H02K 7/09 (2006.01)

(52) **U.S. Cl.**
CPC ***F04D 13/027*** (2013.01); ***F04D 13/0633*** (2013.01); ***F04D 13/064*** (2013.01); ***F04D 25/026*** (2013.01); ***F04D 29/058*** (2013.01); ***F16C 32/0461*** (2013.01); ***F16C 32/0465*** (2013.01); ***F16C 32/0468*** (2013.01); ***F16C 32/0478*** (2013.01); ***H02K 7/09*** (2013.01); *F16C 32/041* (2013.01); *F16C 32/0412* (2013.01); *F16C 32/0417* (2013.01); *F16C 32/0421* (2013.01)

(58) **Field of Classification Search**
CPC F04D 13/064; F04D 25/026; F04D 25/062; F04D 25/0633; F04D 29/058; F16C 32/0412; F16C 32/0465; F16C 32/0461; F16C 32/0468; F16C 32/0478
See application file for complete search history.

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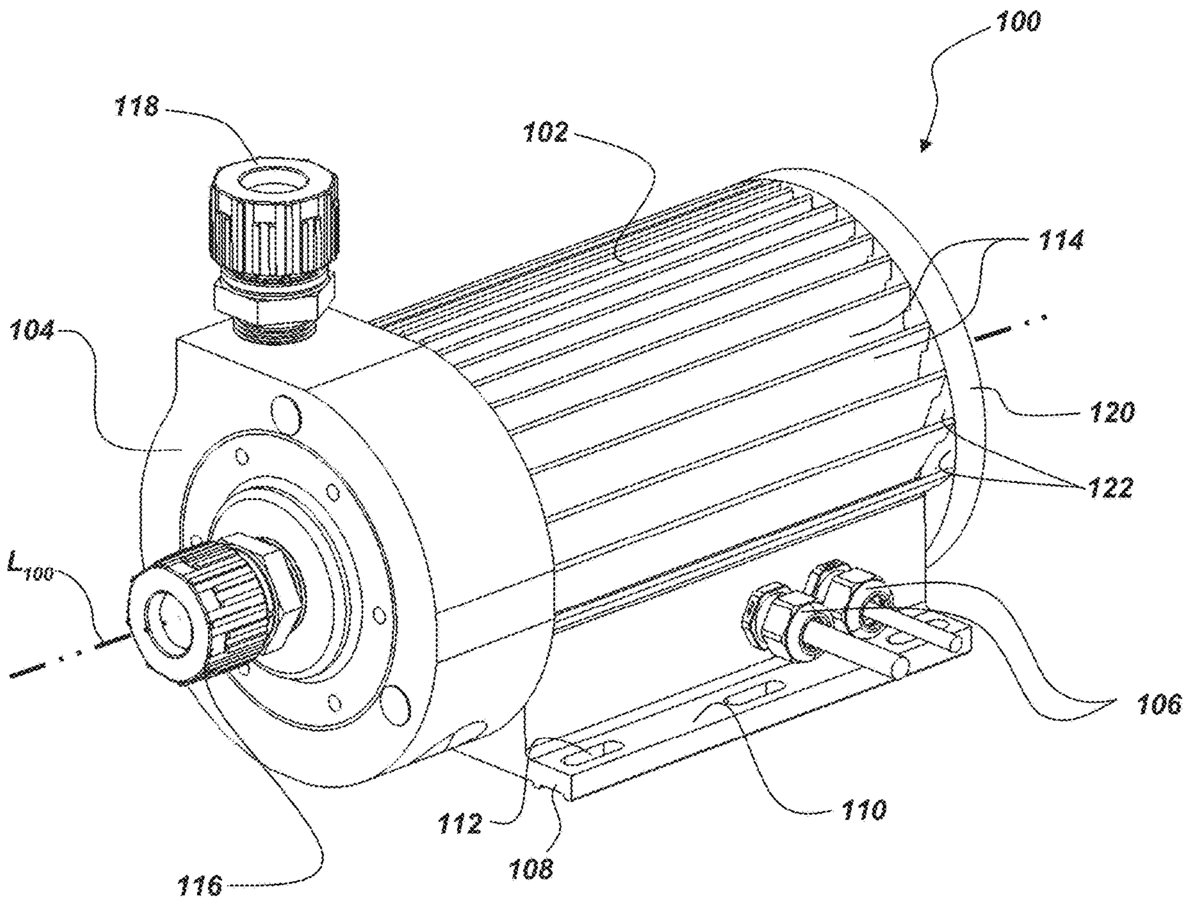

FIG. 1

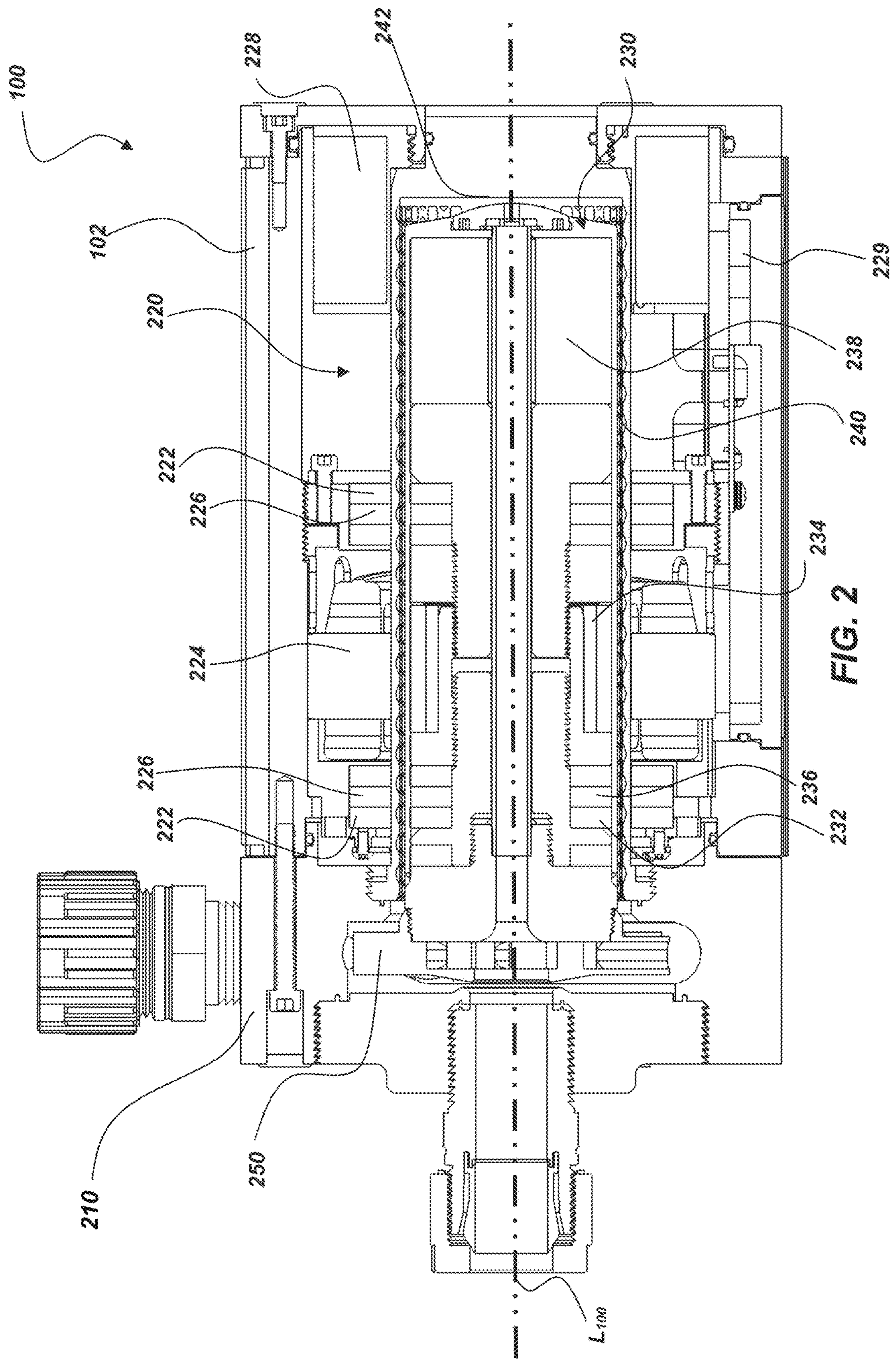
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FIG. 2

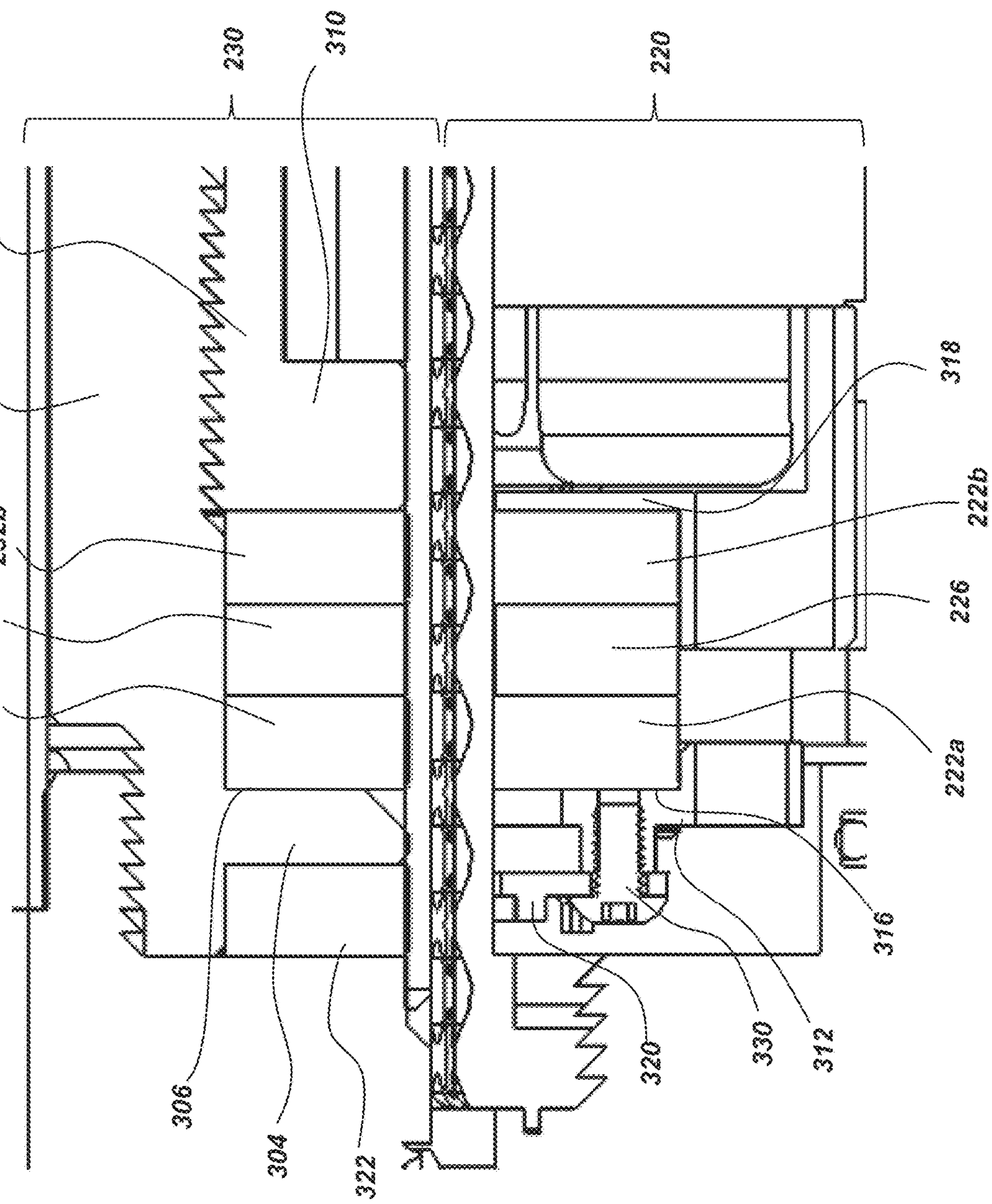
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FIG. 3

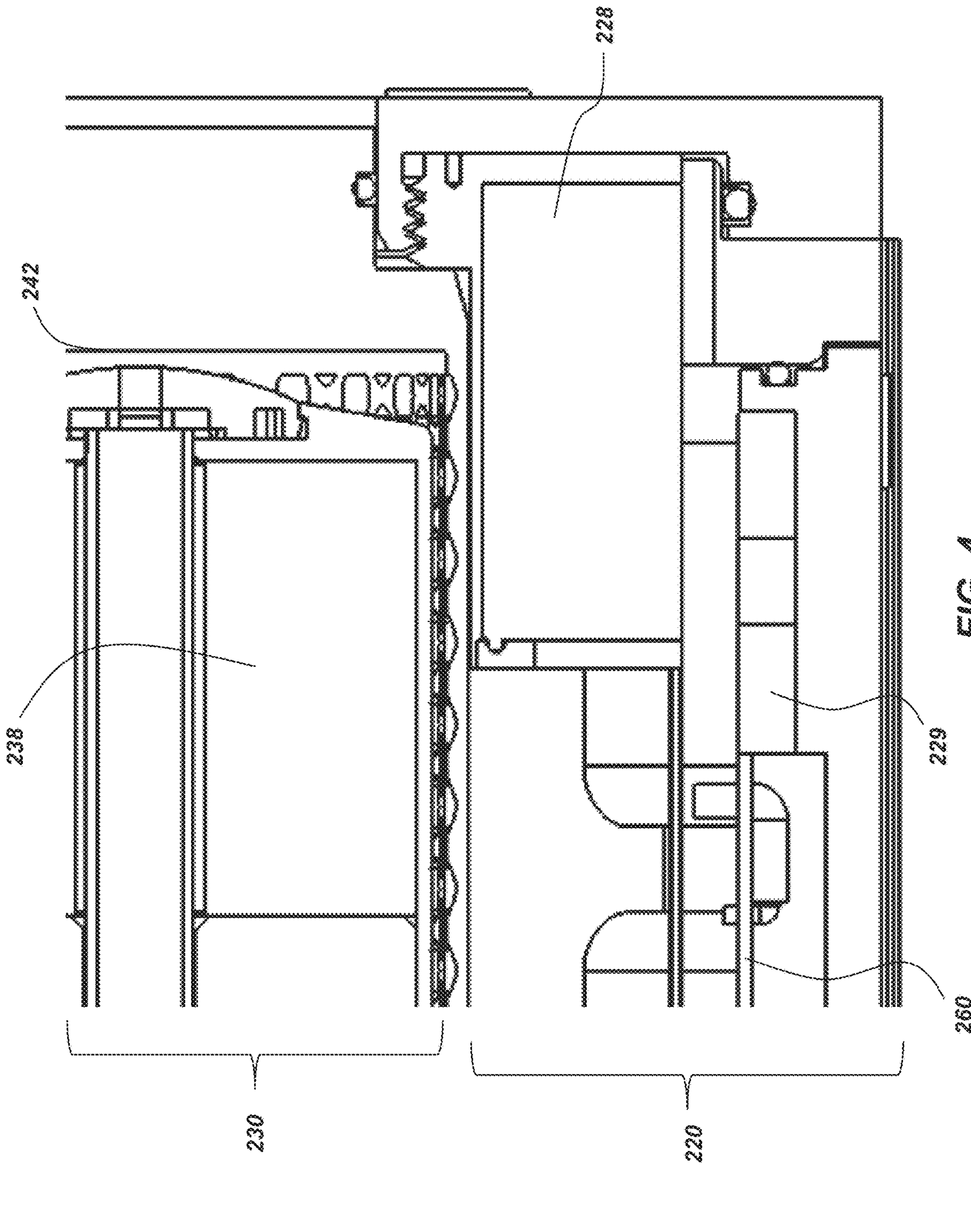

FIG. 4

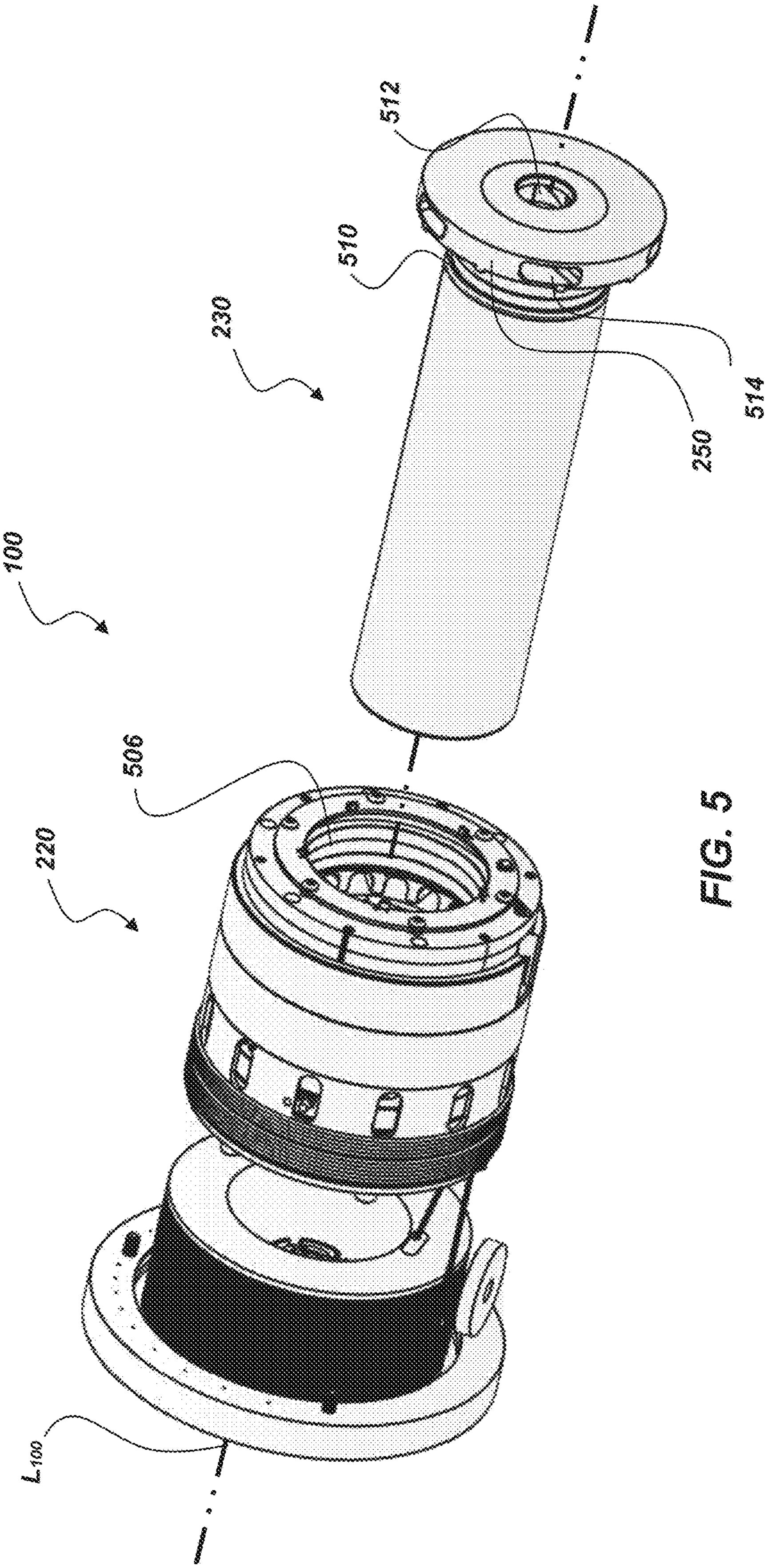

FIG. 5

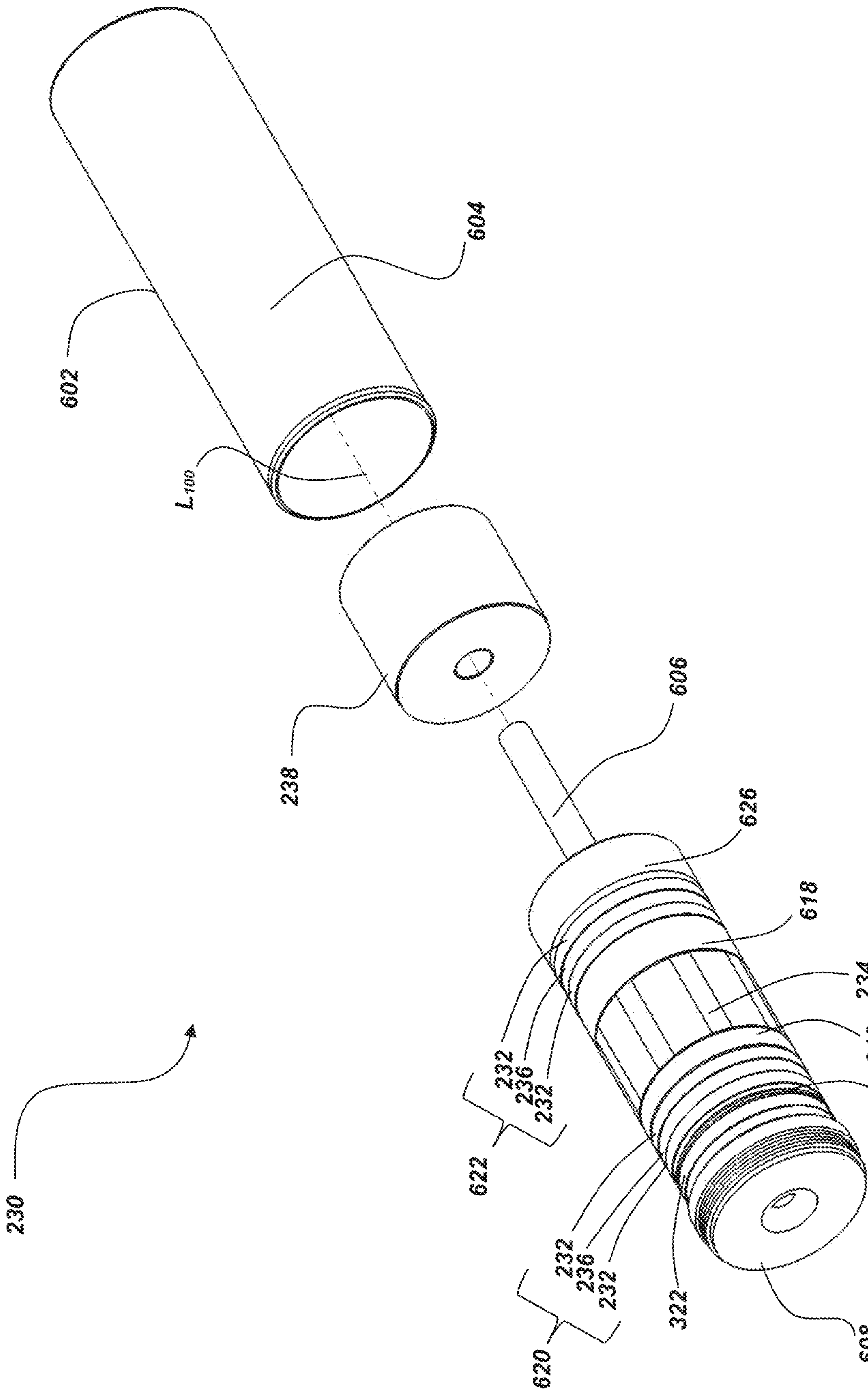

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FIG. 6

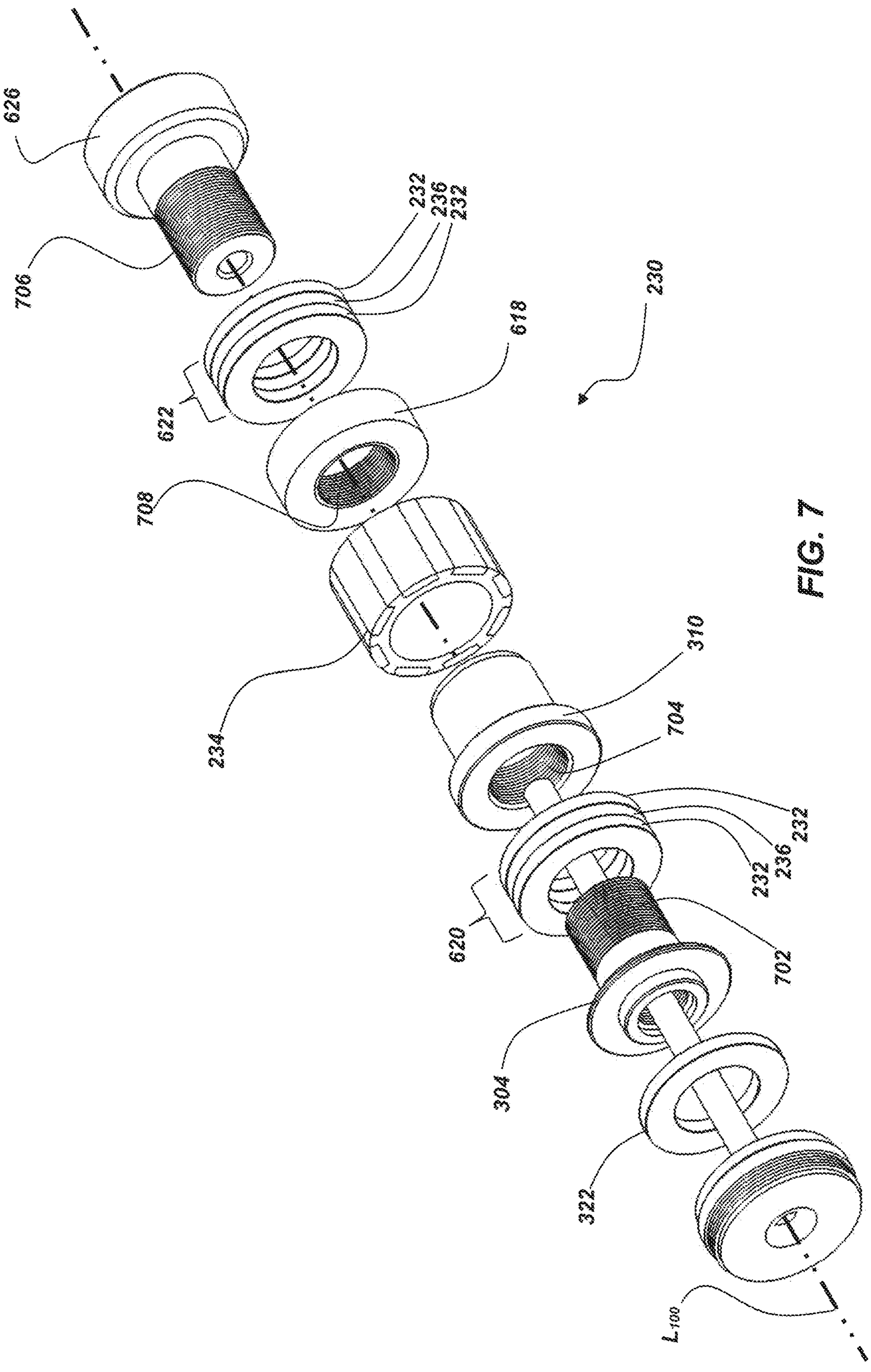
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FIG. 7

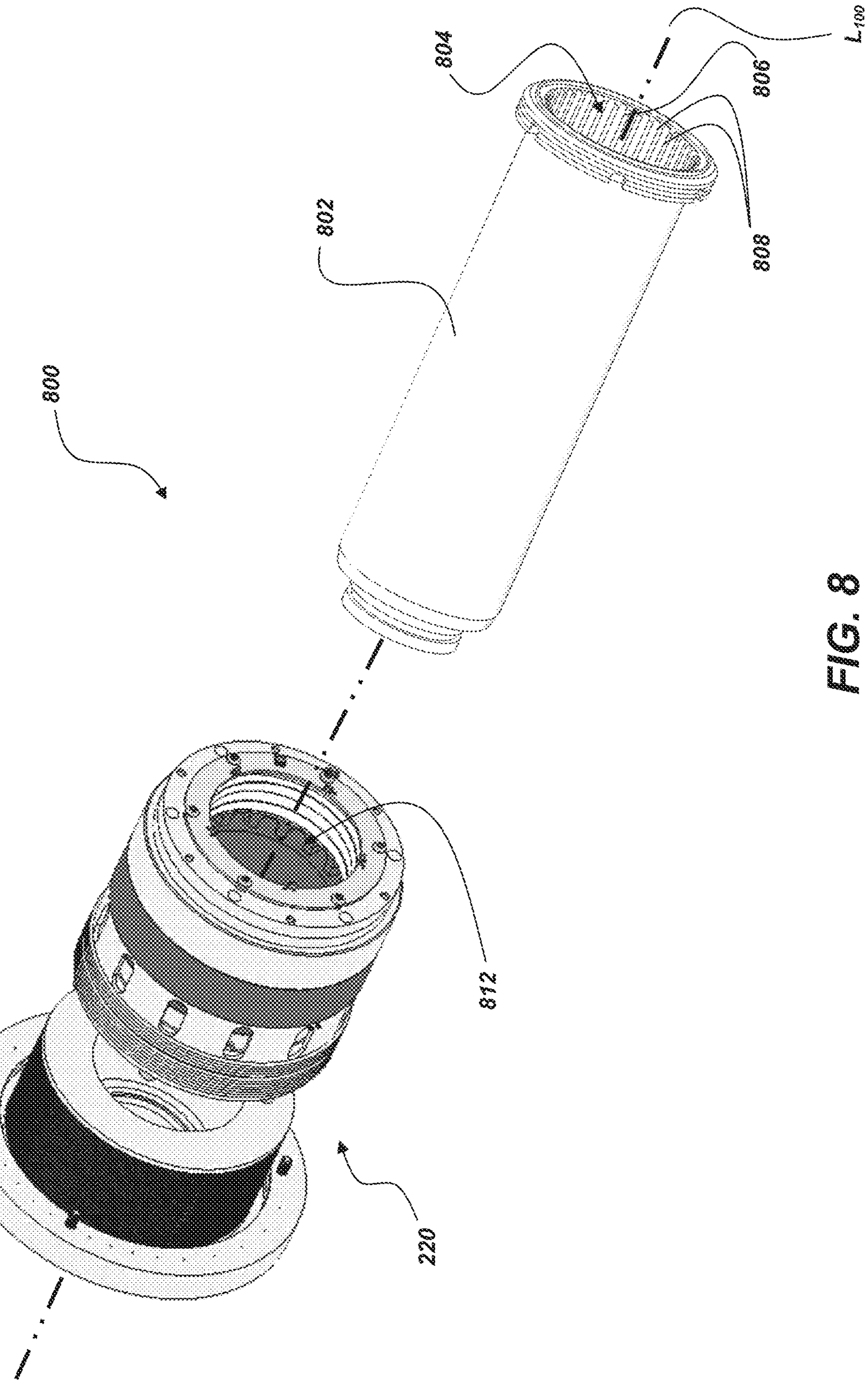

FIG. 8

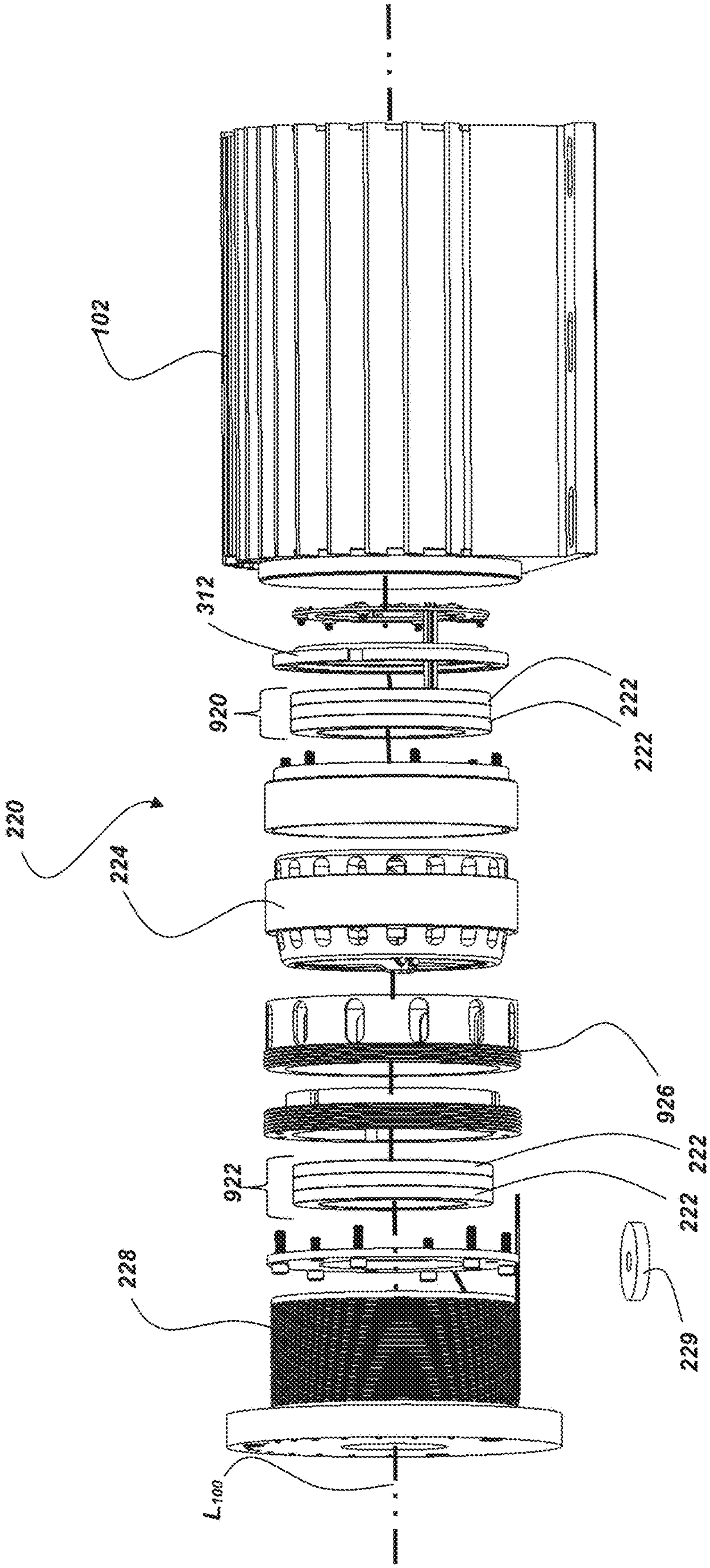

FIG. 9

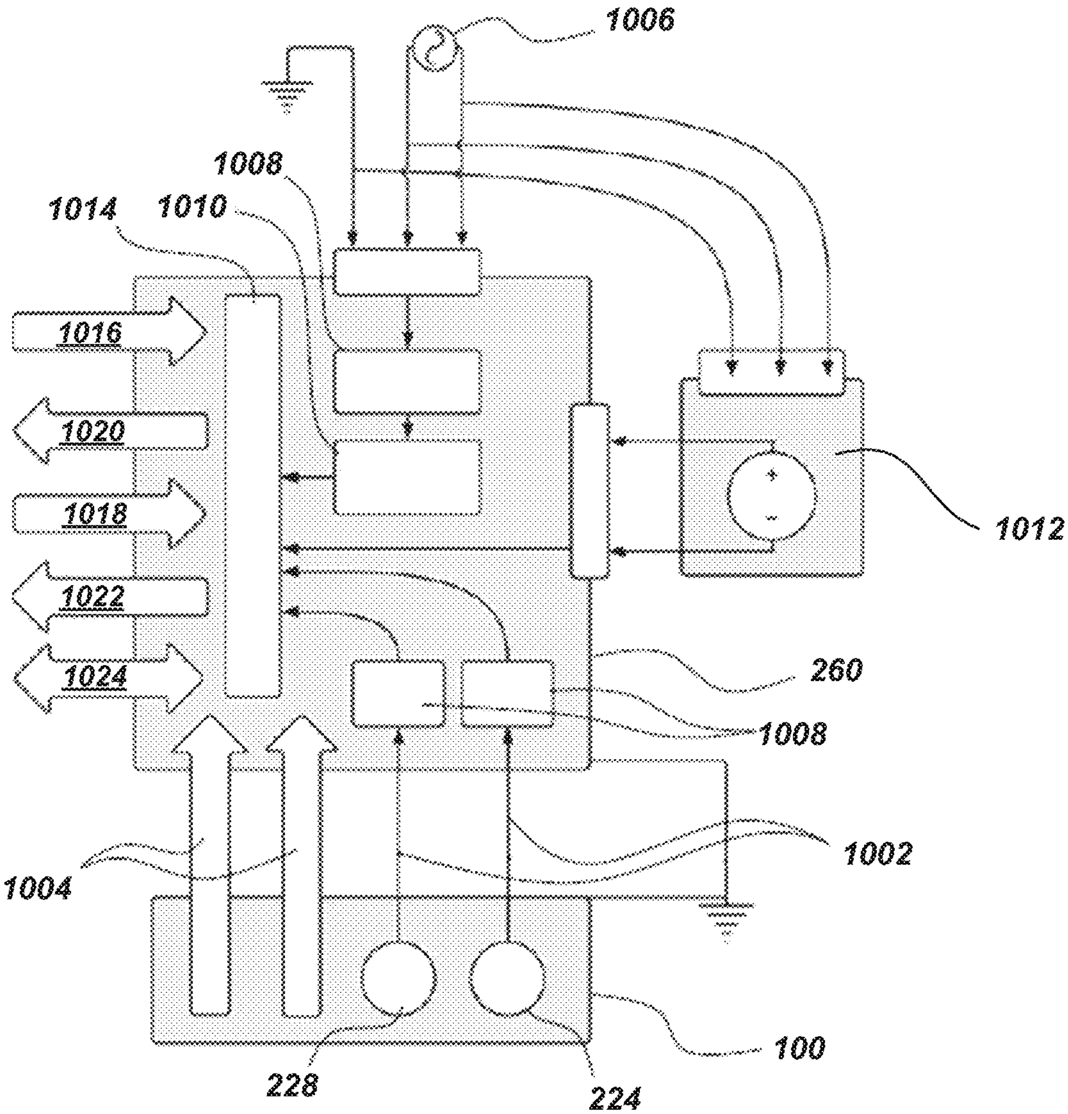
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FIG. 10

PUMP HAVING OPPOSING MAGNETS BETWEEN A ROTOR AND STATOR, AND RELATED ASSEMBLIES, SYSTEMS, AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 16/779,944, filed Feb. 3, 2020, now U.S. Pat. No. 11,421,694 issued Aug. 23, 2022, which claims the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Patent Application Ser. No. 62/800,264, filed Feb. 1, 2019, the disclosure of each of which is hereby incorporated herein in its entirety by this reference.

TECHNICAL FIELD

The present disclosure relates generally to pumps for pumping liquids that include bearingless electromagnetic motors having a rotor and a stator, and in which magnets are used for journaling of the rotor within the stator, and to related methods of manufacturing and using such pumps.

BACKGROUND

Bearingless pumps generally include an impeller that is journaled by magnetic forces in a sealed pump housing. The pumps are generally driven by a rotating magnetic field generated by electromagnets carried by a stator within the pump housing. Such pumps are "bearingless" in the sense that they do not include conventional mechanical bearings, although magnets are used in to perform the journaling of the impeller (or rotor) within the stator. Bearingless pumps may be advantageous for applications in which the fluid to be conveyed must remain pure (e.g., not contaminated), for example, biological fluids (e.g., blood), or pure liquids (e.g., ultrapure water).

Bearingless pumps are also useful for conveying aggressive liquids (e.g., alkaline fluids, acidic fluids, caustic fluids, abrasive fluids, etc.) that would otherwise destroy or degrade mechanical bearings. Therefore, bearingless pumps are preferred for use in applications such as chemical-mechanical polishing, water treatment, processing operations, etc.

BRIEF SUMMARY

Various embodiments may include a pump including a stator, a rotor, and an impeller. The stator may include a drive magnet and one or more permanent magnets positioned on opposing axial ends of the drive magnet. The stator may also include at least one axial positioning magnet positioned at a first axial end of the stator. The rotor may be disposed coaxially within the stator. The rotor may include an armature aligned with the drive magnet and one or more complementary permanent magnets aligned with the one or more permanent magnets. The rotor may also include a push/pull magnet positioned at a first axial end of the rotor. The one or more complementary permanent magnets of the rotor and the one or more permanent magnets of the stator may be configured to create one or more magnetic bearings. The pull magnet may be configured to interact with the at least one axial positioning magnet to position the rotor in an axial direction relative to the stator. The armature and the drive magnet may be configured to rotate the rotor with respect to the stator. The impeller may be coupled to the rotor at a second axial end of the rotor opposite the first axial end. The impeller may be configured to rotate with the rotor.

Another embodiment of the present disclosure may be a pump assembly including an electric motor and an impeller. The electric motor may include a rotor, at least two magnetic bearings, and a positioning magnet assembly. The rotor may be configured to rotate relative to a stator. A drive magnet in the stator may be configured to impart a rotational force on a permanent magnet in the rotor. The at least two magnetic bearings may be positioned on opposing ends of the drive magnet in the stator. The at least two magnetic bearings may include at least two complementary permanent magnets. The at least two complementary permanent magnets may include a rotating permanent magnet and a stationary permanent magnet. The rotating permanent magnet may be attached to the rotor on opposing ends of the rotor and the stationary permanent magnets may be attached to the stator on opposing ends of the drive magnet. The positioning magnet assembly may be in a first longitudinal end of the electric motor. The positioning magnet assembly may include an electromagnetic axial positioning magnet coupled to the stator and a permanent push/pull magnet coupled to the rotor. The electromagnetic axial positioning magnet may be configured to interact with the permanent push/pull magnet to generate a force on the rotor in a direction along a longitudinal axis of the electric motor. The impeller may be coupled to the rotor on a longitudinal end of the rotor opposite the first longitudinal end of the electric motor.

Another embodiment of the present disclosure may be a method of controlling a rotor position in a magnetically levitated pump. The method may include sensing an axial position of a rotor relative to a stator with a position sensor. The method may further include outputting a voltage to a locating electromagnet positioned on an axial end of the rotor to position of the rotor at a position set-point. The method may also include sensing a current at a locating electromagnet. The method may further include comparing the current to a current set-point. The difference between the current and the current set-point may then be produced. The method may also include outputting an adjustment to the position set-point to correct the difference.

BRIEF DESCRIPTION OF THE DRAWINGS

While the specification concludes with claims particularly pointing out and distinctly claiming what are regarded as embodiments of the present disclosure, various features and advantages of embodiments of the disclosure may be more readily ascertained from the following description of example embodiments of the disclosure when read in conjunction with the accompanying drawings, in which:

FIG. **1** is an isometric view of a pump according to an embodiment of the present disclosure;

FIG. **2** is a cross-sectional view of the pump illustrated in FIG. **1**;

FIGS. **3** and **4** are enlarged views of portions of the cross-sectional view of the embodiment of the pump illustrated in FIG. **2**;

FIG. **5** is an exploded view of a stator and rotor assembly of the pump illustrated in FIGS. **1**-**4**;

FIG. **6** is a partially exploded view of the rotor assembly illustrated in FIG. **5**;

FIG. **7** is an exploded view of a portion of the rotor assembly illustrated in FIG. **6**;

FIG. **8** is a partially exploded view of the stator assembly illustrated in FIG. **5**;

FIG. **9** is an exploded view of a portion of the stator assembly illustrated in FIG. **8**; and

FIG. **10** is a schematic view of a control system according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

The illustrations presented herein are not meant to be actual views of any particular pump or component thereof, but are merely idealized representations employed to describe illustrative embodiments of the present disclosure. The drawings are not necessarily to scale. Elements common between figures may retain the same numerical designation.

As used herein, relational terms, such as "first," "second," "top," "bottom," etc., are generally used for clarity and convenience in understanding the disclosure and accompanying drawings and do not connote or depend on any specific preference, orientation, or order, except where the context clearly indicates otherwise.

As used herein, the term "and/or" means and includes any and all combinations of one or more of the associated listed items.

As used herein, the terms "vertical" and "lateral" refer to the orientations as depicted in the figures.

As used herein, the term "substantially" or "about" in reference to a given parameter means and includes to a degree that one skilled in the art would understand that the given parameter, property, or condition is met with a small degree of variance, such as within acceptable manufacturing tolerances. For example, a parameter that is substantially met may be at least about 90% met, at least about 95% met, at least about 99% met, or even 100% met.

As used herein, the term "magnetic material" means and includes ferromagnetic materials, ferrimagnetic materials, antiferromagnetic, and paramagnetic materials.

Bearingless pumps (e.g., magnetically levitated pumps, etc.) may provide multiple advantages. The removal of traditional bearings may result in reduced frictional losses due to friction inherent in typical bearing and seal combinations. The removal of traditional bearings may also increase the operating time (e.g., lifespan) of pump components before the pump must be rebuilt or replaced due to worn parts. Removing the traditional bearings also introduces additional variables into the bearingless pump that are traditionally remedied by the traditional bearings. For example, traditional bearings may locate the rotating portion of the pump (e.g., shaft, impeller, rotor, etc.) both radially (e.g., about a central axis) and longitudinally (e.g., axially, laterally, along the central axis). Magnetic bearings may also locate the rotating portion of the pump both axially and longitudinally; however, the magnetic bearings may allow the rotating portion of the pump to move (e.g., shift, slip, displace, etc.) by larger distances than a traditional mechanical bearing. In some applications, the additional movement may be undesirable and/or may result in additional wear, damaged parts, and other potential problems.

FIG. **1** illustrates an embodiment of a pump **100** according to the present disclosure. The pump **100** may include a body **102** and a pump housing **104**. The body **102** may include a motor (e.g., a D.C. motor, an A.C. motor, etc.) and/or drive components for the pump **100**. The body **102** may include ports **106** that enable power and/or electrical signals (e.g., electricity) to be conveyed from an external power source and/or controller/drive to the motor within the body **102**. The body **102** may include a mounting structure **108**.

The mounting structure **108** may be used to secure the pump **100** to a stationary object (e.g., wall, floor, mounting pad, structure, frame, etc.). In some embodiments, the mounting structure **108** may include a flange **110** having at least one hole **112** (e.g., slot, opening, etc.) extending therethrough. The hole **112** may be configured to receive mounting hardware such as bolts, studs, screws, straps (e.g., metal straps, polymer straps, cloth straps, nylon straps, band straps, clamping straps, etc.), cables, brackets, hooks, etc. In some embodiments, the mounting structure **108** may include integral mounting hardware (e.g., studs, clamps, threaded inserts, etc.).

The body **102** may also include one or more fins **114** (e.g., protrusions, plates, etc.) extending from the body **102**. In some embodiments, the fins **114** may be configured to aid in transferring heat from the motor (e.g., cooling the motor) or other components inside the body **102**. The fins **114** may be linear (e.g., substantially straight) and extend radially outward from the body **102**, and may be oriented parallel to a longitudinal axis of the body **102**, as shown in FIG. **1**. In some embodiments, the fins **114** may be substantially circular (e.g., annular, etc.) extending circumferentially about a central axis L_{100} (e.g., in a series of rings, spiral, helix, etc.).

The pump housing **104** may include a back plate **120**. The back plate **120** may include one or more cooling ports **122**. The cooling ports **122** may be configured to direct fluid (e.g., air, water, etc.) flow over the fins **114**. In some embodiments, the cooling ports **122** may be configured to direct passive fluid flow. In some embodiments, an auxiliary device such as a fan or pump may be coupled to the back plate **120** and configured to force fluid flow through the cooling ports **122** and over the fins **114**. For example, the auxiliary device may be configured to draw fluid through the cooling ports **122** such that the fluid may flow over the fins **114** and then be drawn through the cooling ports **122** by the auxiliary device. In some embodiments, the auxiliary device may be configured to force fluid through the cooling ports **122** and then over the fins **114**.

The pump housing **104** may include an inlet port **116** and an outlet port **118**. The pump housing **104** may house an impeller (e.g., rotor, paddle, propeller, turbine, etc.) configured to receive a fluid through the inlet port **116** and output the fluid through the outlet port **118**. In some embodiments, the impeller may be configured to pressurize the fluid to a higher pressure than the fluid at the inlet port **116** before outputting the fluid through the outlet port **118** (e.g., a pump). In other embodiments, the impeller may be configured to receive the fluid at a high pressure through the inlet port **116** and output the fluid at a lower pressure through the outlet port **118**. The high pressure fluid may cause the impeller to rotate converting the pressure of the fluid into rotational energy which may then be converted into, electrical energy or some other form of mechanical energy.

FIG. **2** illustrates a cross-sectional view of the pump **100**. The body **102** may enclose a stator assembly **220**, pump housing assembly **210**, and a rotor assembly **230**. The stator assembly **220** may include one or more permanent magnets **222** and one or more drive magnets **224**. The drive magnets **224** may be, for example, electromagnets, windings, a commutator, a coil, an armature, etc., configured to generate a magnetic field around the rotor assembly **230**. The one or more permanent magnets **222** may be substantially annular (e.g., ring shaped, circular, etc.). The permanent magnets **222** may rest against spacers **226** (e.g., shims, annular rings, etc.). The stator assembly **220** may further include a pull magnet **228** and a lift magnet **229**. The pull magnet **228** and the lift magnet **229** may be configured to control or maintain a position of the rotor assembly **230** relative to the stator. In some embodiments, at least one of the pull magnet **228** and the lift magnet **229** may be an electromagnet. In some embodiments, at least one of the pull magnet **228** and the lift magnet **229** may be a permanent magnet.

The rotor assembly **230** may include one or more complementary permanent magnets **232**, an armature **234**, spacers **236**, and a complementary pull magnet **238**. The complementary permanent magnets **232** and the armature **234** may be substantially annular in shape. The armature **234** may be, for example, a coil, windings, a conductor, a permanent magnet, etc., configured to generate a rotational force on the rotor assembly **230** from the magnetic field generated by the drive magnets **224**. The complementary permanent magnets **232** may be substantially aligned with the permanent magnets **222** of the stator assembly **220** in an axial direction, along a longitudinal axis L_{100}. The complementary pull magnet **238** may not be substantially aligned with the pull magnet **228** of the stator assembly **220** in the axial direction.

In some embodiments, the magnetic fields generated by the permanent magnets **222** and the complementary permanent magnets **232** may form passive bearings (e.g., magnetic bearings, contactless bearings, etc.). For example, the permanent magnets **222** and the complementary permanent magnets **232** may be configured to induce a repelling force between the permanent magnets **222** and the complementary permanent magnets **232**. The repelling force may cause the rotor assembly **230** to float within the stator assembly **220**, such that the rotor assembly **230** does not physically contact the stator assembly **220** at any point. Such contactless interaction may reduce frictional losses within the motor. Additionally, a pathway **240** (e.g., passage, path, etc.) may be created between the rotor assembly **230** and the stator assembly **220** such that fluid may pass therethrough. The fluid may be a lubricating fluid, a cooling fluid, a cleansing fluid, a flushing fluid, a blow-by fluid, or any other type of fluid.

In some embodiments, at least one of the permanent magnets **222** and the complementary permanent magnets **232** may be formed from a relatively high strength magnetic material. The high strength magnetic material may have a maximum energy product of at least about 5 MGOe, such as at least about 42 MGOe, at least about 52 MGOe, or combinations therebetween. In some embodiments, at least one of the permanent magnets **222** and the complementary permanent magnets **232** may be formed from a magnetic material such as, alnico (e.g., alloys of aluminum, nickel, and cobalt), neodymium alloys, or samarium cobalt alloys.

In some embodiments, the pull magnet **228** and the complementary pull magnet **238** may be configured to control the axial position of the rotor assembly **230** with respect to the stator assembly **220**. For example, the pull magnet **228** may be configured to induce a force in the axial direction on the complementary pull magnet **238**, as described in more detail below with respect to FIG. **4**. The pull magnet **228** and the complementary pull magnet **238** may be controlled by an electronic controller. For example, a controller **260** may be housed within the stator assembly **220**. In some embodiment, the electronic controller may be positioned externally (e.g., separate from the stator assembly **220**).

An impeller **250** may be connected (e.g., attached, coupled, etc.) to the rotor assembly **230**, such that any rotation of the rotor assembly **230** is imparted to the impeller **250** and/or any rotation of the impeller **250** is imparted to the rotor assembly **230**. The impeller **250** may be connected to the rotor assembly **230** through a mechanical connection such as, bolts, studs, screws, keys, threads (e.g., pipe thread, straight threads, etc.). In some embodiments, the impeller **250** may be connected to the rotor assembly **230** with an adhesive (e.g., glue, epoxy, etc.) or a physiochemical process (e.g., soldering, welding, etc.). In some embodiments, the impeller **250** may be connected to the rotor assembly **230** through an interference connection (e.g., pressed fit, friction fit, etc.). In some embodiments, the impeller **250** may be connected to the rotor assembly **230** by a combination of elements or methods as described above.

In some embodiments, energy may be transferred between the armature **234** and the drive magnets **224** as the rotor assembly **230** rotates relative to the stator assembly **220**. For example, electricity may be applied to the drive magnets **224** which may induce a rotational force on the armature **234**. The rotational force may cause the rotor assembly **230** to rotate relative to the stator. In another embodiment, rotation of the impeller **250** may cause the rotor assembly **230** to rotate relative to the stator. As the armature **234** rotates relative to the drive magnets **224**, the armature **234** may induce an electrical current in the drive magnets **224** generating electrical energy.

FIG. **3** illustrates an enlarged view of the permanent magnet **222** and complementary permanent magnet **232** of the embodiment of the pump **100** in FIG. **2**. The rotor assembly **230** may include multiple structural sections configured to retain and separate different parts of the rotor assembly **230**. For example, the rotor assembly **230** may include a front support **302** with a front retaining structure **304** configured to retain the complementary permanent magnets **232** on a first axial end **306**. A first complementary permanent magnet **232***a* may be positioned against the front retaining structure **304**. The spacer **236** may be positioned between the first complementary permanent magnet **232***a* and a second complementary permanent magnet **232***b*. The second complementary permanent magnet **232***b* may be secured in place by an armature support **308**. The armature support **308** may include front central spacer **310** configured to sandwich the first and second complementary permanent magnets **232***a*, **232***b* and the spacer **236** between the front retaining structure **304** and the front central spacer **310**.

In some embodiments, the space between the front retaining structure **304** and the front central spacer **310** may be adjustable. For example, the armature support **308** may thread onto the front support **302**. In some embodiments, the armature support **308** may be a collar with threads on an inner surface of the armature support **308** that are configured to interface with threads on an exterior surface of the front support **302**. In some embodiments, the interfacing surfaces between the front support **302** and the armature support **308** may be relatively smooth, such that the armature support **308** is able to slide axially along the front support **302**. The armature support **308** and the front support **302** may clamp the first and second complementary permanent magnets **232***a*, **232***b*, and the spacer **236** between the front retaining structure **304** and the front central spacer **310** with separate hardware (e.g., bolt, screw, stud, spring clamp, screw clamp, etc.).

The permanent magnets **222** in the stator assembly **220** may include a similar retaining structure. For example, the stator assembly **220** may include a front retaining element **312** configured to contact a leading end **316** of a first permanent magnet **222***a* and a secondary front retaining element **318** configured to sandwich a second permanent magnet **222***b* and the first permanent magnet **222***a* as well as the spacer **226** between the front retaining element **312** and the secondary front retaining element **318**. In some embodiments, the front retaining element **312** and the secondary front retaining element **318** may be clamped together using a bolted connection. In other embodiments, the front retaining element **312** and the secondary front retaining element **318** may be clamped together with a threaded connection, or other connections similar to those outlined above with respect to the armature support **308** and the front support **302**. In some embodiments, the front retaining element **312** and the secondary front retaining element **318** may be part of the stator assembly **220**. In some embodiments, the front retaining element **312** and the secondary front retaining element **318** may be part of the body **102**. In some embodiments, the front retaining element **312** and the secondary front retaining element **318** may be a combination of parts of the body **102** and parts of the stator assembly **220**.

In some embodiments, a position sensor **320** may be positioned in the stator assembly **220** substantially aligned with a position indicator **322**. In some embodiments, the position indicator **322** may be a permanent magnet. In some embodiments, the position indicator **322** may be another element configured to interact with the position sensor **320**, such as a heated element, a reflective element, etc. The position sensor **320** may configured to produce a signal corresponding to an axial position of rotor assembly **230** in relation to stator assembly **220**. In some embodiments, the sensor **320** may be a magnetic proximity sensor, a Hall Effect sensor, an ultrasonic sensor, an inductive sensor, a laser sensor, a photo sensor, a capacitive sensor, an infrared sensor, etc. In some embodiments, the controller **260** may monitor the signal from the position sensor **320**. The controller **260** may control the axial position of the rotor assembly **230** by adjusting the power to the pull magnet **228** as described in detail below, to adjust the axial force on the rotor assembly **230**.

The position sensor **320** may be coupled to the front retaining element **312** through a connection **330**. In some embodiments, the connection **330** may be a bolted connection as shown in FIG. **3**. In some embodiments, the connection **330** may be an adhesive connection, such as glue or epoxy. In some embodiments, the connection **330** may be a clamped connection, such as a spring clamp, a bolted clamp, etc.

In some embodiments, there may be more than one position sensor **320**, such as between 1 sensor and 10 sensors, between 1 sensor and 5 sensors, or between 1 sensor and 3 sensors. In some embodiments, the controller **260** may monitor an average axial position from all of the sensors. For example, the controller **260** may receive individual readings from each sensor of the position sensors **320** and average the readings from the position sensors **320** internally. In some embodiments, the position sensors **320** may be wired into an averaging circuit, providing a single averaged input to the controller **260**.

In some embodiments, the controller **260** may monitor the position sensors **320** individually and determine a minimum value, maximum value, average value, median value, etc. In some embodiments, the controller **260** may be configured to perform different operations with the different values. For example, the controller **260** may produce an alarm (e.g., audible alarm, alarm signal, dry contact alarm, safety circuit, etc.) when the maximum or minimum value from the position sensor **320** are above or below defined thresholds. In some embodiments, the threshold values may be defined in positions such that the alarms may stop operation of the pump **100** before damage occurs.

The controller **260** may be configured to control the axial position of the rotor assembly **230** to within about 0.5 mm, or even within about 0.25 mm.

FIG. **4** illustrates an enlarged view of the pull magnet **228** and the complementary pull magnet **238** of the embodiment of the pump **100** shown in FIG. **2**. The magnetic fields generated by the pull magnet **228** and the complementary pull magnet **238** may generate an axial force on the rotor assembly **230**. The pull magnet **228** may be an electromagnet such that the axial force may be adjusted to maintain the rotor assembly **230** in a desired axial position. For example, the pull magnet **228** may generate an increased axial force toward pump housing surface **242** if the rotor assembly **230** and complementary pull magnet **238** move in an axial direction away from pump housing surface **242**. Alternatively, the pull magnet **228** may decrease the axial force or even induce a repelling force pushing the complementary pull magnet **238** and rotor assembly **230** away from pump housing surface **242**, if the rotor is too close or touching pump housing surface **242**. In some embodiments, pump housing surface **242** may be a hard stop configured to maintain the axial position of the rotor assembly **230** within tolerances, such that damage to critical components of the rotor assembly **230**, such as the impeller **250**, is substantially prevented.

In some embodiments (e.g., when the pump **100** is installed with the axis of the stator in the vertical direction), lift magnet **229** will not be part of the assembly. In other embodiments (e.g., when the pump **100** is installed with the axis of the stator in the horizontal plane), lift magnet **229** may be a permanent magnet configured to repel the complementary pull magnet **238**. The lift magnet **229** may be positioned at an end of the stator assembly **220** near complementary pull magnet **238**. The lift magnet **229** may introduce a load on the rotor assembly **230**. The load may increase as the complementary pull magnet **238** travels radially down in the direction of gravity and decrease as the complementary pull magnet **238** travels radially up in the direction of gravity.

In some embodiments, the amps required to turn the rotor assembly **230** may be monitored. For example, the pump **100** may include internal circuitry or controls that may monitor the amps at the drive magnets **224** (FIG. **2**). For example, an internal circuit may isolate the wiring traveling to the drive magnets **224** from other electrical components in the pump **100**. A sensor (e.g., current transducer, resistance sensor, fiber optic sensor, hall-effect sensor, etc.) may monitor the isolated circuit and the controls or internal circuitry may monitor the amps in the isolated circuit, record and log the amps in the isolated circuit, and/or control another component of the pump based on the amps in the isolated circuit. In some embodiments, some or all of the control may be located externally, such that a sensor may be positioned in or on the power input into the pump **100** and analyzed by an external controller. In some embodiments, the revolutions of rotor assembly **230** may be monitored.

In some embodiments, the axial position of the rotor assembly **230** may be controlled by increasing or decreasing the power to the pull magnet **228**. For example, as rotor assembly moves axially away from its position set-point, the amps provided to pull magnet **228** may increase or decrease. The increase or decrease in power will change the pull magnets **228** interaction with the complementary pull magnet **238** and will alter the position of rotor assembly **230**, moving rotor assembly **230** back to its position set-point.

The power to the pull magnet **228** may be controlled through a control algorithm such as a PID loop, step and wait algorithm, closed loop control, feed-forward control, etc. The control algorithm may include a position set-point and a current set-point for the amps going to the pull magnet **228**. For example, the control algorithm may monitor the position of the position indicator **322** compared to the position sensor **320** and compare the position to the position set-point. The control algorithm may then make appropriate adjustments to the power to the pull magnet **228** to correct any differences between the monitored position of the position indicator **322** and the position set-point. The control algorithm may then compare the amps going to the pull magnet **228** to the current set-point and adjust the position set-point accordingly based on a calculated difference between the actual amps and the current set-point. In some embodiments, the current set-point may be a set number that is anticipated to be the lowest power required to levitate the rotor assembly **230** in pump **100**. For example, the current set-point may be between about 0 amps and about 12 amps, such as between about 5 amps and about 10 amps, or about 7 amps. In some embodiments, the control algorithm may minimize the power usage, making adjustments through a control loop until a minimum power usage is reached (e.g., such that any adjustment results in an increase in power usage).

In some embodiments, the axial position of the rotor assembly **230** may be controlled through a combination of monitoring the pull magnet **228** amps and the position sensor **320**.

FIG. **5** illustrates an exploded view of the pump **100**. The stator assembly **220** and rotor assembly **230** may be substantially coaxial about the axis L_{100}. The rotor assembly **230** may be configured to be at least partially disposed into a bore **506** defined by the stator assembly **220**. An impeller **250** may be attached to the rotor assembly **230** at a first end **510** of the rotor assembly **230**. The rotor assembly **230** may be configured to rotate within the bore **506** of the stator assembly **220**. The impeller **250** may be configured to rotate with the rotor assembly **230**. The impeller **250** may be configured to draw fluid in through an inlet **512** and output the fluid at a higher pressure through the vanes **514** (e.g., blades, flutes, etc.). In some embodiments, the vanes **514** may be configured to provide a relatively higher volume of flow at a lower pressure. In other embodiments, the vanes **514** may be configured to provide a relatively lower volume of flow at a higher pressure. The rotational speed of the rotor assembly **230** may also affect the flow volume and/or pressure of the fluid.

FIG. **6** illustrates a partially exploded view of the rotor assembly **230**, which functions as a drive shaft for the impeller **250** (FIG. **2**). The rotor assembly **230** may be encased within a shell **602**. The shell **602** may also provide a surface over which a fluid (e.g., cooling fluid, lubricating fluid, flushing fluid, cleaning fluid, etc.) may flow without directly contacting internal components of the rotor assembly **230**. In some embodiments, the shell **602** may be formed from a non-ferrous material such as, a polymer (e.g., polytetrafluoroethylene (PTFE), polyvinylchloride (PVC), etc.), a non-ferrous metal (e.g., aluminum, copper, stainless steel, etc.), etc. In some embodiments, the shell **602** may be formed from a corrosion resistant material (e.g., polymers, aluminum, etc.) or have a corrosion resistant coating (e.g., rubber coating, polymer coating, etc.).

In some embodiments, an outer surface **604** may be a smooth surface. In some embodiments, the outer surface **604** may include a pattern of raised or recessed features (e.g., dimples, ridges, vanes, grooves, fins, etc.).

The rotor assembly **230** may be concentrically assembled over a central shaft **606**. In some embodiments, the central shaft **606** may be hollow. For example, the central shaft **606** may define an opening, passage, or pathway through a longitudinal length of the shaft **606**. The fluid may flow through the central shaft. For example, the fluid may circulate around the outer surface **604** of the shell **602** and then through the central shaft **606** or the fluid may first pass through the central shaft **606** and then exit around the outer surface **604** of the shell **602**.

The central shaft **606** may be connected (e.g., attached, coupled, etc.) to a front connecting element **608**. In some embodiments, the central shaft **606** may be attached to the front connecting element **608** with hardware (e.g., screws, bolds, studs, rivets, pins, etc.). In some embodiments, the central shaft **606** may be attached to the front connecting element **608** with an adhesive (e.g., glue, epoxy, etc.), weld, or solder. In some embodiments, the central shaft **606** may be attached to the front connecting element **608** through an interference fit (e.g., press fit, friction fit, etc.). In some embodiments, the central shaft **606** may be formed as part of the front connecting element **608**. For example, the central shaft **606** may be extruded or drawn from the front connecting element **608**, or the front connecting element **608** and the central shaft **606** may be formed in a process such as forging or molding. In some embodiments, the central shaft **606** may be attached to the front connecting element **608** through a combination of several attachment means. In some embodiments, the shell **602** may be configured to connect to the front connecting element **608** by welding, gluing, a threaded connection, mechanical fasteners, etc.

The front connecting element **608** may be configured to attach the rotor assembly **230** to the impeller **250** (FIG. **5**). In some embodiments, the front connecting element **608** may provide a threaded connection (e.g., pipe threads, machine threads, external threads, internal threads, etc.) for connecting to the impeller **250** (FIG. **5**). In some embodiments, the front connecting element **608** may provide hardware (e.g., studs, pins, key stock, etc.) or hardware receiving features (e.g., holes, threaded holes, grooves, tracks, etc.) for connecting to the impeller **250** (FIG. **5**). In some embodiments, the front connecting element **608** may provide a surface configured to be pressed into the impeller **250** (FIG. **5**) (e.g., an interference fit). In some embodiments, the front connecting element **608** may be configured to attach to the impeller **250** (FIG. **5**) through a combination of connecting features.

Following the front connecting element **608**, the rotor assembly **230** may include a pattern of complementary permanent magnets **232** and spacers **236**. The complementary permanent magnets **232** may be configured to interact with the corresponding permanent magnets **222** in the stator assembly **220** (FIGS. **2**, **5**, and **9**) to form magnetic bearings. The spacers **236** may be configured to position the complementary permanent magnets **232** in the correct axial position and maintain the complementary permanent magnets **232** in position once the rotor assembly **230** is assembled. The spacers **236** may have different thicknesses at different locations to define the correct axial positions of the complementary permanent magnets **232**. The complementary permanent magnets **232** and spacers **236** may be arranged to form a front magnetic bearing assembly **620** and a rear magnetic bearing assembly **622**. Each of the front magnetic bearing assembly **620** and the rear magnetic bearing assembly **622** may include at least one complementary permanent magnet **232** and at least one spacer **236**. In some embodiments, the front magnetic bearing assembly **620** may include at least two complementary permanent magnets **232** separated by at least one spacer **236**. Similarly, the rear magnetic bearing assembly **622** may include at least two complementary permanent magnets **232** separated by at least one spacer **236**. In another embodiment, at least one of the front magnetic bearing assembly **620** and the rear magnetic bearing assembly **622** may include at least three complementary permanent magnets **232** separated by at least two spacers **236**. In some embodiments, the front magnetic bearing assembly **620** and/or rear magnetic bearing assembly **622** may include additional complementary permanent magnets **232**, such as four, five, six, or more complementary permanent magnets **232**. Similarly, the front magnetic bearing assembly **620** and/or rear magnetic bearing assembly **622** may include additional spacers **236**, such as three, four, five, six, or more spacers **236**.

In some embodiments, adjacent complementary permanent magnets **232** in one or more of the front magnetic bearing assembly **620** and the rear magnetic bearing assembly **622** may be oriented with opposing polarities such that the adjacent complementary permanent magnets **232** induce a repulsive force between the adjacent complementary permanent magnets **232** in the rotor assembly **230** pushing the complementary permanent magnets **232** against the front and/or rear central spacers **310**, **618** and/or the front and/or rear retaining structure **304**, **626**. In some embodiments, adjacent complementary permanent magnets **232** in one or more of the front magnetic bearing assembly **620** and the rear magnetic bearing assembly **622** may be oriented with the same polarities such that the adjacent complementary permanent magnets **232** induce an attracting force between the adjacent complementary permanent magnets **232** in the rotor assembly **230** pulling the complementary permanent magnets **232** against the spacer **236** between the adjacent complementary permanent magnets **232**.

The position indicator **322** may be positioned on an end of one of the front magnetic bearing assembly **620** and the rear magnetic bearing assembly **622**. For example, the position indicator **322** may be positioned ahead of the front magnetic bearing assembly **620**, between the front magnetic bearing assembly **620** and the front connecting element **608**. The position indicator **322** may be configured to interact with the position sensor **320** in the stator assembly **220** (FIG. **3**).

The armature **234** may be disposed between two central spacers **310**, **618**. The front central spacer **310** may be positioned between the armature **234** and the front magnetic bearing assembly **620**. A rear central spacer **618** may be positioned between the armature **234** and the rear magnetic bearing assembly **622**. The assembly of front and rear magnetic bearing assemblies **620**, **622**, central spacers **310**, **618**, and the armature **234** may be secured between the front retaining structure **304** and a rear retaining structure **626**.

The armature **234** may be configured to convert magnetic impulses provided by the stator assembly **220** (FIG. **5**) into rotation. The armature **234** may be secured to the rotor assembly **230** in such a way that the rotation of the armature **234** may also rotate the entire rotor assembly **230**. In some embodiments, the armature **234** may be secured to the central shaft **606** such that the rotation of the armature **234** is transmitted directly to the central shaft **606** and the central shaft transmits the rotation to the front connecting element **608** and other rotating elements. In some embodiments, the armature **234** may be secured to at least one of the front central spacer **310** and the rear central spacer **618** which may be connected to the corresponding front and/or rear magnetic bearing assembly **620**, **622**. The front and/or rear magnetic bearing assemblies **620**, **622** may be connected to the respective front or rear retaining structure **304**, **626**. The front retaining structure **304** may be connected to at least one of the central shaft **606** and/or the front connecting element **608** and the rear retaining structure **626** may be connected to the central shaft **606**. In such an embodiment, the armature **234** may transmit the rotation through the series of interconnected parts to the central shaft **606** and/or the front connecting element **608**.

The rotor assembly **230** may include a complementary pull magnet **238** located behind (e.g., to the rear, following, etc.) the rear retaining structure **626**. The complementary pull magnet **238** may be configured to interact with at least one corresponding pull magnet **228** (FIGS. **2** and **9**) in the stator assembly **220** (FIG. **5**) to maintain and/or correct an axial position of the rotor assembly **230** within the stator assembly **220** (FIG. **5**). In some embodiments, the complementary pull magnet **238** may be secured to the central shaft **606**. In some embodiments, the complementary pull magnet **238** may be secured to the rear retaining structure **626**. In some embodiments, the complementary pull magnet **238** may be secured to the rotor assembly **230** by the shell **602**.

In some embodiments, the rotor assembly **230** may be configured to be disassembled and reassembled with ease, such that individual components, such as the complementary permanent magnets **232**, spacers **236**, armature **234**, complementary pull magnet **238**, etc., may be removed and replaced when necessary. For example, the individual components may be replaced when the individual component is worn, broken, or otherwise defective. In some embodiments, the rotor assembly **230** may be configured to be replaced as a unit. For example, the rotor assembly **230** may be removed from the stator assembly **220** (FIG. **5**) and a replacement rotor assembly **230** may be inserted in its place. In some embodiments, the rotor assembly **230** may be both replaceable as a unit and rebuildable.

FIG. **7** illustrates an exploded view of a portion of the rotor assembly **230** illustrated in FIG. **6**. The front retaining structure **304** may include an external interfacing structure **702** such as threads (e.g., pipe threads, machine threads, etc.), grooves, ridges, tabs, etc., configured to interface with a complementary internal interfacing structure **704** in the front central spacer **310**. The complementary internal interfacing structure **704** may be configured to receive the external interfacing structure **702** of the front retaining structure **304** securing the front retaining structure **304** to the front central spacer **310**.

The distance between the front retaining structure **304** and the front central spacer **310** may be defined by the interface between the external interfacing structure **702** and the complementary internal interfacing structure **704**. In some embodiments, the distance between the front retaining structure **304** and the front central spacer **310** may be constant (e.g., the distance remains the same each time the rotor assembly **230** is assembled regardless of a size of the front magnetic bearing assembly **620**). In some embodiments, the distance between the front retaining structure **304** and the front central spacer **310** may be adjustable. For example, a threaded interface between the external interfacing structure **702** and the complementary internal interfacing structure **704** may allow the distance between the front retaining structure **304** and the front central spacer **310** to change as the front retaining structure **304** is threaded into or out of the front central spacer **310**.

The rear retaining structure **626** may also include an external interfacing component **706**. In some embodiments, the rear central spacer **618** may include a complementary internal interfacing component **708** configured to interface with the external interfacing component **706**. In some embodiments, the external interfacing component **706** may be configured to interface with the complementary internal interfacing structure **704** of the front central spacer **310**.

The distance between the rear retaining structure **626** and the rear central spacer **618** may be defined by the interface between the external interfacing component **706** and the complementary internal interfacing component **708**. In some embodiments, the distance between the rear retaining structure **626** and the rear central spacer **618** may be constant (e.g., the distance remains the same each time the rotor assembly **230** is assembled regardless of a size of the rear magnetic bearing assembly **622**). In some embodiments, the distance between the rear retaining structure **626** and the rear central spacer **618** may be adjustable, such as with a threaded interface.

The distance between the rear retaining structure **626** and the front central spacer **310** may be defined by the interface between the external interfacing component **706** and the complementary internal interfacing structure **704**. In some embodiments, the distance between the rear retaining structure **626** and the front central spacer **310** may be constant (e.g., the distance remains the same each time the rotor assembly **230** is assembled regardless of a size of the rear magnetic bearing assembly **622** combined with the rear central spacer **618** and the armature **234**). In some embodiments, the distance between the rear retaining structure **626** and the front central spacer **310** may be adjustable, such as with a threaded interface.

In some embodiments, the interface between the external interfacing component **706** of the rear retaining structure **626** and the complementary internal interfacing component **708** of the rear central spacer **618** may be a floating connection. For example, the rear central spacer **618** may be slidably connected to the rear retaining structure **626** such that the rear central spacer **618** may move axially relative to the rear retaining structure **626**. The distance between the rear retaining structure **626** and the rear central spacer **618** may be defined by intermediary components between the rear retaining structure **626** and the front central spacer **310**, such as the armature **234** and/or the rear magnetic bearing assembly **622**.

FIG. **8** illustrates an exploded view of a stator assembly **800** and a stator sleeve **802** (e.g., housing, isolator, wall, etc.). The stator sleeve **802** is secured to the pump housing and configured to be disposed between the rotor assembly **230** (FIG. **5**) and the stator assembly **800**. The rotor assembly **230** (FIG. **5**) may be inserted into a bore **804** of the stator sleeve **802**. In some embodiments, the bore **804** may be sized to provide a clearance fit (e.g., slightly larger, a small percentage larger, etc.) to the rotor assembly **230** (FIG. **5**). For example, the bore **804** may be sized such that an internal diameter of the bore **804** is between about 5 μm and about 5 mm larger than an external diameter of the rotor assembly **230** (FIG. **5**) such as between about 2 mm and about 4 mm larger.

The stator sleeve **802** may include a pattern of raised or recessed features **808** (e.g., dimples, ridges, vanes, grooves, fins, etc.) on an interior surface **806** (e.g., surface facing the rotor assembly **230** (FIG. **5**)) of the stator sleeve **802**. The patterns on the interior surface **806** may at least partially (e.g., partially, substantially, completely, etc.) reduce rotational flow of fluid that may be present and/or flowing between the rotor assembly **230** (FIG. **5**) and the interior surface **806** of the stator sleeve **802**. Rotational flow of fluids in rotating assemblies may cause harmonic vibrations at certain rotational speeds (e.g., oil whirl, oil whip, fluid whip, etc.). Harmonic vibrations may be destructive if not corrected. The pattern of raised or recessed features may substantially reduce destructive vibrations introduced by the rotational flow.

The stator sleeve **802** may be at least partially disposed within the stator assembly **220**. The stator sleeve **802** may be configured to isolate the stator assembly **220** from the rotor assembly **230** (FIG. **5**). In some embodiments, the stator sleeve **802** may be configured to enable fluid to flow around the rotor assembly **230** (FIG. **5**) while substantially preventing the fluid from contacting the stator assembly **220**. In some embodiments, the stator sleeve **802** may be configured to shield the stator assembly **220** from contact or debris in the event that a failure occurs with the rotor assembly **230** (FIG. **5**) (e.g., the rotor assembly **230** (FIG. **5**) breaks, the rotor assembly **230** (FIG. **5**) is improperly aligned, etc.). The stator sleeve **802** may be formed from a strong non-ferrous material such as, a polymer (e.g., polytetrafluoroethylene (PTFE), polyvinylchloride (PVC), etc.), a non-ferrous metal (e.g., aluminum, copper, etc.), etc. In some embodiments, the stator sleeve **802** may be formed from a corrosion resistant material (e.g., polymers, aluminum, etc.) or have a corrosion resistant coating (e.g., rubber coating, polymer coating, etc.).

The stator assembly **220** may be formed from an assembly of annular components defining an opening **812** configured to receive the stator sleeve **802**. In some embodiments, the annular components of the stator assembly **220** may be mounted (e.g., secured, attached, etc.) to the stator sleeve **802**. In some embodiments, the annular components of the stator assembly **220** may be mounted to an external body, housing, or casing (e.g., body **102** (FIG. **1**)). In some embodiments, the annular components of the stator assembly **220** may be attached to the other annular components of the stator assembly **220**. In some embodiments, the annular components of the stator assembly **220** may be attached to a combination of the elements described above.

FIG. **9** illustrates an exploded view of the stator assembly **220** of FIG. **8**. The annular components of the stator assembly **220** may include a front magnetic bearing assembly **920**, a rear magnetic bearing assembly **922**, the drive magnets **224**, a front retaining element **312**, a rear retaining structure **926**, and the pull magnet **228**. The front magnetic bearing assembly **920** and the rear magnetic bearing assembly **922** may each include at least one permanent annular magnet **222**. In some embodiments, the annular components may be positioned using spacers similar to those described above with respect to the rotor assembly **230** shown in FIGS. **6** and **7**. In some embodiments, the spacers may be integrated into mounting structure such as the body **102** (FIG. **2**).

Referring to FIGS. **6**, **8**, and **9**. The front and rear magnetic bearing assemblies **920**, **922** may be configured to interact with the front and rear magnetic bearing assemblies **620**, **622** of the rotor assembly **230**. For example, the front and rear magnetic bearing assemblies **920**, **922** of the stator assembly **220** may be positioned (e.g., spaced) such that each permanent magnet **222** is aligned with the corresponding complementary permanent magnet **232** of the rotor assembly **230**. In some embodiments, each permanent magnet **222** may be oriented such that the polarity (e.g., north pole, south pole) of the permanent magnet **222** is aligned with the polarity of the corresponding complementary permanent magnet **232** of the rotor assembly **230**, such that a repelling force is induced by the magnetic field between the permanent magnet **222** and the corresponding complementary permanent magnet **232**. In some embodiments, each permanent magnet **222** may be oriented such that the polarity of the permanent magnet **222** is opposite the polarity of the corresponding complementary permanent magnet **232** of the rotor assembly **230**, such that an attracting force is induced by the magnetic field between the permanent magnet **222** and the corresponding complementary permanent magnet **232**. In some embodiments, some of the permanent magnets **222** may be oriented with the polarities aligned with the corresponding complementary permanent magnets **232** of the rotor, while others may be oriented with the polarities opposite the corresponding complementary permanent magnets **232**. For example, the permanent magnets **222** of the front magnetic bearing assembly **920** may be oriented with the polarities aligned with the corresponding complementary permanent magnets **232** of the front magnetic bearing assembly **620** of the rotor assembly **230** and the permanent magnets **222** of the rear magnetic bearing assembly **922** may be oriented with the polarities opposite the corresponding complementary permanent magnets **232** of the rear magnetic bearing assembly **622**. In another example, each of the front and rear magnetic bearing assemblies **920**, **922** may include at least one permanent magnet **222** oriented with the polarity aligned with the corresponding complementary permanent magnet **232** of the rotor assembly **230** and at least one permanent magnet **222** oriented with the polarity opposite the corresponding complementary permanent magnet **232** of the rotor assembly **230**.

In some embodiments, adjacent permanent magnets **222** in one or more of the front magnetic bearing assembly **920** and the rear magnetic bearing assembly **922** may be oriented with the same polarities such that the adjacent permanent magnets **222** induce a repulsive force between the adjacent permanent magnets **222** in the stator assembly **220**. In some embodiments, adjacent permanent magnets **222** in one or more of the front magnetic bearing assembly **920** and the rear magnetic bearing assembly **922** may be oriented with opposing polarities such that the adjacent permanent magnets **222** induce an attracting force between the adjacent permanent magnets **222** in the stator assembly **220**.

The drive magnet assembly **224** may be substantially aligned with the armature **234** of the rotor assembly **230** and configured to interact with the armature **234**. For example, an electrical current may be supplied to the drive magnets **224**. The drive magnets **224** may generate a magnetic field from the electrical current which may induce a rotational force on the armature **234**. The electrical current may originate from an external source (e.g., generator, line power, transformer, inverter, motor controller, variable frequency drive, etc.). In some embodiments, internal circuitry (e.g., control board, motor controller, speed controller, etc.) may modify the electrical current. In some embodiments, the pump may include the controller **260** that may divert some of the electrical current to power and operate the controller **260** and/or other components of the pump. In some embodiments, the controller **260** and other components such as the complementary pull magnet **228** may be powered separately from the pump, such as through an independent power supply. The controller **260** may modify the electrical current (e.g., change amplitude, frequency, voltage, amps, etc.) before sending the electrical current to the drive magnets **224**. In some embodiments, the controller **260** may monitor the electrical current being supplied to the drive magnet **224**. In some embodiments, the controller **260** may control other components of the pump based on the current being supplied to the drive magnet **224**. For example, the controller **260** may monitor the amps being supplied to the drive magnet **224** and may control the current being supplied to the pull magnet **228** based on the amps being supplied to the drive magnet **224**.

FIG. **10** illustrates a schematic view of a control system for the pump **100**. The control system may include the controller **260**. In some embodiments, the controller **260** may be integrated with the pump **100**. In some embodiments, the controller **260** may be external to the pump **100**. For example, the controller **260** may be coupled to the pump **100** through the electrical cables **1002** and/or signal wires **1004** passing into the pump **100** through the ports **106** (FIG. **1**). For example, the electrical cables **1002** may provide power to one or more of the drive magnet **224** and/or the pull magnet **228**.

The controller **260** may control the power passing to the drive magnet **224** and/or the pull magnet **228**. For example, line voltage power **1006**, such as 110 Volts Alternating Current (VAC), 120 VAC, 208 VAC, 240 VAC, 277 VAC, 480 VAC, etc., may pass through the controller **260**. In some embodiments, the line voltage power **1006** may be single phase power, dual phase power, or three phase power. The controller **260** may be configured to process the line voltage power **1006**. For example, the controller **260** may include a filter **1008**. The filter **1008** may be configured to filter noise out of the line voltage power **1006**, such as power spikes. In some embodiments, the filter **1008** may be configured to detect problems in the line voltage power **1006**, such as brown outs, loss of a phase, power spikes, etc. In some embodiments, the filter **1008** may be configured to interrupt power if a problem is detected such that internal components of the controller **260** and/or the pump **100** may be protected from the line voltage power **1006**. In some embodiments, the controller **260** may include a power converting device **1010**. For example, the power converting device **1010** may be configured to convert alternating current power to direct current power (e.g., rectifier) or direct current power to alternating current power (e.g., inverter). In some embodiments, the power converting device **1010** may be configured to change a voltage and/or amperage of the line voltage power **1006** (e.g., transformer).

In some embodiments, the controller **260** may include one or more drives configured to control the power passing through the controller **260** to the drive magnet **224** and/or the pull magnet **228** with one or more drives **1012**. For example, the controller **260** may include variable frequency drives (VFDs) configured to adjust a frequency of the power passing to the drive magnet **224** and/or the pull magnet **228**. Adjusting the frequency may enable the controller **260** to control a speed of the armature and/or a magnetic field generated by the pull magnet **228**. In some embodiments, the drives **1012** may control the power to the drive magnet **224** and/or the pull magnet **228** by selectively switching the power from the controller **260** on and off, thus reducing the power being supply from the controller **260**.

In some embodiments, the controller **260** may only control power to one of the drive magnet **224** and/or the pull magnet **228**. For example, the controller **260** may be configured to control the axial position of the rotor assembly **230** by controlling power to the pull magnet **228** independent of the power being supplied to the drive magnet **224**. The controller **260** may monitor the axial position of the rotor assembly **230** through the position sensor **320** and control the power to the pull magnet **228** accordingly. The power to the drive magnet **224** may be controlled and monitored independently, such that the speed, pressure, and/or flow of the pump may be controlled independent of the axial position of the rotor assembly **230**.

The controller **260** may include a user interface **1014**. In some embodiments, the user interface **1014** may be a display, such as a touch screen, monitor, screen, etc. In some embodiments, the user interface **1014** may be a communication module configured to communicate with a remote computing device, such as a control system, building management system (BMS), personal computer, laptop, server, cloud, etc.

The controller **260** may be configured to receive analog inputs **1016** and/or digital inputs **1018**. For example, the controller **260** may be configure to receive analog inputs **1016** such as, set points, process feedback, system requirements, system sensor readings, etc. The digital inputs **1018** may include a system enable, pump enable, reset, control enable, alarm, system safety (e.g., high pressure, high temperature, low temperature, low pressure, manual kill switch, etc.), etc. In some embodiments, the analog inputs may be signals such as voltage signals (e.g., 0-5 VDC, 0-10 VDC, etc.), resistance signals (e.g., resistance temperature detectors (RTD), etc.), or current signals (e.g., 0-20 milliamp (mA), 4-20 mA, etc.).

The controller **260** may be configured to provide analog outputs **1020** and/or digital outputs **1022** to other components and/or to a user. For example, the controller **260** may provide analog outputs **1020** and/or digital outputs **1022** may be provided to the user through the display device such as through a graphic user interface (GUI), a spread sheet, a series of lights, etc. The analog outputs **1020** and/or digital outputs **1022** may be provided to other components through signals such as voltage signals (e.g., 0-10 VDC, 0-5 VDC, 10-30 VDC, etc.) or current signals (e.g., 4-20 mA, 0-20 mA, etc.). In some embodiments, the analog outputs **1020** may include motor speed, rotor position, set points, etc. The digital outputs **1022** may include motor status, errors, alarms, etc. In some embodiments, the controller **260** may receive motor information such as, sensor readings (e.g., motor temperature, rotor position, motor speed, etc.) from sensors within the pump **100**. For example, the position sensor **320** (FIG. **3**) may be provide the rotor position to the controller **260** directly through the signal wires **1004** or through a communication interface in the controller **260**.

The controller **260** may also include a network connection **1024**. The network connection **1024** may be configured to connect the controller **260** and/or the user interface **1014** to additional controllers and/or system devices, such as redundant pumps, complementary devices, control devices, etc. For example, the pump **100** may be controlled through a system level control system, such as a BMS system, plant control system, process control system, etc. The controller **260** may be configured to communicate information from the pump **100** and/or controller **260** to the system through the network connection **1024**. In some embodiments, the network connection may be a communication cable connection, such as RS 232 (e.g., serial), RS 485, RJ45 (e.g., Ethernet), RJ11, RJ14, RJ25, etc.

In some embodiments, the controller **260** may monitor additional features in the motor. The controller **260** may use sensors, such as temperature sensors (e.g., resistance temperature detectors (RTD), negative temperature coefficient (NTC), thermocouple, etc.), position sensors (e.g., hall-effect, proximity, induction, etc.), current sensors (e.g., transducer, hall-effect, etc.), etc. The controller **260** may relay the sensor readings to an external source (e.g., monitoring system, display, alarming system, control system, etc.). In some embodiments, the controller **260** may perform operations, such as change pump speed, change operation and/or parameters of other components (e.g., pull magnet **228**, etc.), produce an alarm, stop the pump, etc., based on readings.

While bearingless pumps may experience higher efficiencies due to friction reduction, that friction reduction may not result in reduced wear. For example, bearingless pumps may allow for increased axial movement of the rotor which may result in harmful vibrations. Additionally, the higher rotational speeds that are achievable with reduced friction may introduce additional harmful vibrations. Embodiments of the present disclosure may control (e.g., reduce, substantially reduce, eliminate, etc.) the harmful vibrations inherent in bearingless pumps. Reducing the harmful vibrations may result in increased operational lifespans, decreased downtime for repairs, and decreased operational and repair expenses. Some embodiments of the present disclosure may also reduce the amount of downtime experienced when a pump fails or needs to be rebuilt or repaired.

In some environments, pumps are used in critical systems where having a pump down due to a failure could result in catastrophic failure of a system. In other systems, having a pump down due to failure may result in large financial losses. Increasing the operational lifespan of a pump and/or reducing the amount of downtime when repairs are needed may result in a reduction of financial burdens on operations utilizing pumps, because in critical systems redundancies may be reduced and in high value systems financial losses may be reduced and/or avoided.

While the present disclosure has been described herein with respect to certain illustrated embodiments, those of ordinary skill in the art will recognize and appreciate that it is not so limited. Rather, many additions, deletions, and modifications to the illustrated embodiments may be made without departing from the scope of the disclosure as hereinafter claimed, including legal equivalents thereof. In addition, features from one embodiment may be combined with features of another embodiment while still being encompassed within the scope of the disclosure as contemplated by the inventors.

What is claimed is:

1. A magnetically levitated electric motor comprising:

a rotor comprising an armature and one or more permanent magnets on opposing axial sides of the armature;

a stator substantially coaxial with the rotor, the stator comprising a drive magnet axially aligned with the armature and one or more complementary permanent magnets positioned on opposing axial sides of the drive magnet; a permanent push/pull magnet positioned on an axial end of the rotor;

a locating electromagnet positioned on an axial end of the stator, configured to position of the rotor at a position set-point by interacting with the push/pull magnet, the locating electromagnet axially offset from the push/pull magnet;

a permanent lift magnet positioned on the axial end of the stator, the permanent lift magnet configured to support the axial end of the rotor; and

wherein at least one of the one or more complementary permanent magnets is located between the locating electromagnet and the drive magnet.

2. The magnetically levitated electric motor of claim **1**, further comprising a position sensor in the stator and a corresponding position indicator in the rotor.

3. The magnetically levitated electric motor of claim **2**, wherein the locating electromagnet is configured to be controlled based on information from the position sensor.

4. The magnetically levitated electric motor of claim **2**, wherein the position sensor is positioned on a second axial end of the stator opposite the axial end of the stator corresponding to the locating electromagnet.

5. The magnetically levitated electric motor of claim **2**, wherein the position sensor comprises at least two position sensors.

6. The magnetically levitated electric motor of claim **5**, wherein the at least two position sensors are coupled to an averaging circuit.

7. The electric motor of claim **2**, wherein the position indicator is positioned in the rotor adjacent to the position sensor.

8. The electric motor of claim **2**, further comprising an electronic controller configured to receive a position measurement from the position sensor.

9. The electric motor of claim **8**, wherein the electronic controller is configured to change control parameters of the locating electromagnet based on the position measurement from the position sensor.

10. The electric motor of claim **9**, wherein the electronic controller is configured to adjust power to the locating electromagnet based on the position measurement from the position sensor.

11. The magnetically levitated electric motor of claim **1**, wherein the permanent lift magnet is positioned in the stator proximate the permanent push/pull magnet of the rotor.

12. The magnetically levitated electric motor of claim **1**, wherein the permanent lift magnet is configured to induce a radial force on the permanent push/pull magnet.

13. The magnetically levitated electric motor of claim **1**, wherein the locating electromagnet is positioned radially between the permanent lift magnet and the permanent push/pull magnet.

14. A method of controlling an axial position of a magnetically levitated electric motor, the method comprising:

inducing an axial force on a rotor comprising an armature, one or more permanent magnets on opposing axial sides of the armature, and a permanent lift magnet positioned on the axial end of a stator, the permanent lift magnet configured to support an axial end of rotor, the rotor positioned radially within the stator through a magnetic force between a push/pull magnet positioned on an axial end the rotor and a locating electromagnet positioned on the stator, the stator substantially coaxial with the rotor, the stator comprising a drive magnet axially aligned with the armature and one or more complementary permanent magnets positioned on opposing axial sides of the drive magnet, and the locating electromagnet positioned on the axial end of the stator, configured to position of the rotor at a position set-point by interacting with the push/pull magnet, substantially coaxial with the rotor, and axially offset from the push/pull magnet, wherein at least one of the one or more complementary permanent magnets is located between the locating electromagnet and the drive magnet;

measuring an axial position of the rotor relative to the stator;

adjusting a voltage to the locating electromagnet to change the axial force on the locating permanent magnet; and

inducing a radial force on an axial end of the rotor through a radial magnetic force between the locating magnet and the permanent lift magnet, the radial force configured to support the axial end of the rotor.

15. The method of claim **14**, further comprising:

measuring a current to the drive magnet in the stator; and

adjusting an axial position set-point to position the axial end of the rotor in a position where the radial force induced by the permanent lift magnet minimizes a gravity induced load.

16. The method of claim **14**, wherein adjusting the voltage to the locating electromagnet comprises reversing a polarity of the voltage to the locating electromagnet.

17. The method of claim **14**, wherein measuring the axial position of the rotor relative to the stator comprises receiving a position measurement from a position sensor in the stator.

18. The method of claim **17**, wherein receiving the position measurement from the position sensor comprises detecting a proximity of a position indicator in the rotor to the position sensor.

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